High-Q GaN nanowire resonators and oscillators

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We report high mechanical quality factors Q for GaN nanowire cantilevers grown by molecular beam epitaxy. Nanowires with $30-500$ nm diameters and $5-20$ μm lengths having resonance frequencies from 400 kHz to 2.8 MHz were measured. Q near room temperature and 10^{-4} Pa ranged from 2700 to above 60 000 with most above 10 000. Positive feedback to a piezoelectric stack caused spontaneous nanowire oscillations with Q exceeding 10^6. Spontaneous oscillations also occurred with direct e-beam excitation of unintentionally doped nanowires. Doped nanowires showed no oscillations, consistent with oscillation arising via direct actuation of piezoelectric GaN. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2815747]

Micro- and nanoelectromechanical systems are being investigated for a number of sensing[1–5] and signal processing[6,7] applications. Here, it is desirable to develop systems with minimal energy loss or very high mechanical quality factors Q (defined as the ratio of the resonance frequency to the resonance full width at half maximum power). The Q factors of nanomechanical resonators tend to decrease with decreasing diameter, indicating an increasing importance of surface effects.[8,9] This is an important issue that may limit the utility of nanoelectromechanical resonators and systems and motivates the investigation of alternative materials

Here, we report as-grown c-axis oriented GaN nanowire mechanical Q values of at least ten times higher than those previously reported for systems of similar size.[8–10] Nanowires with surface-to-volume ratios between 0.01 and 0.06 nm^{-1} were measured to have mechanical Q values as high as 6×10^4 at room temperature and 10^{-4} Pa. Q values approached 10^5 at 450 K. Further, we observed stochastic variations in the measured Q for individual nanowires. Such variations suggest that the observed resonance linewidths are inhomogenously broadened by nanoscale parameter fluctuations. Thus, the large Q values observed are unlikely to represent the intrinsic limits for GaN and might be significantly improved.

Our GaN nanowires were grown on Si (111) substrates by gas source molecular beam epitaxy.[11] The wires form spontaneously from a GaN matrix layer under growth conditions (high V-III source constituent ratio) that promote a nanowire (rather than planar) growth mode (Fig. 1). The nanowires we have studied are oriented along the [0001] direction (c-axis orientation) and are approximately perpendicular to the substrate surface. These wires have a number of promising material characteristics including low defect density[12] and high photoluminescence intensity.[13] X-ray diffraction indicates that the c-axis and a-axis lattice parameters are within 0.1% of the lattice parameters of bulk GaN. Transmission electron microscopy reveals the nanowires to be free of dislocations and stacking faults. n-type doping of these nanowires is achieved with Si dopants. Carrier densities

above 10^{18} cm^{-3} have been attained. The wires are unintentionally n-type as grown.

To measure the resonance properties of the nanowires, pieces of the substrate carrying as-grown nanowires were attached to the top of a shear-mode piezoelectric stack (Fig. 2(a)) and placed in a scanning electron microscope (SEM). The resonances of the nanowires can be seen by applying an ac signal to the piezostack at or near the resonance frequency. Figures 2(c) and 2(d) show the time averaged images of the two lowest order vibrational modes for a wire that measured roughly 14 μm long and 0.2 μm in diameter. With the electron beam placed in spot mode and directed onto the edge of a nanowire (Fig. 2(a)), the function generator frequency was scanned through the resonance. The output from the SEM secondary electron detector [scintillator followed by a photomultiplier tube (PMT)] was fed into a rf lock-in amplifier that used the function generator as a reference source [Fig. 2(a), blue lines]. An example of the recorded in-phase and quadrature PMT signal amplitudes versus applied signal frequency is shown in Figs. 2(e) and 2(f). The solid red lines indicate simultaneously fitted real and imaginary parts of a complex Lorentzian resonance response given by $A(\omega^2 - \omega_0^2 + i\omega\Gamma)^{-1}e^{i\phi}$, where Γ is the damping constant and ϕ is an additional phase between the reference signal and the measured response signal determined by the experimental setup. An alternate technique that has been used to characterize the resonance parameters is to use a white noise signal to actuate the piezoelectric stack and record the PMT signal with a real-time spectrum analyzer. Within the uncer-
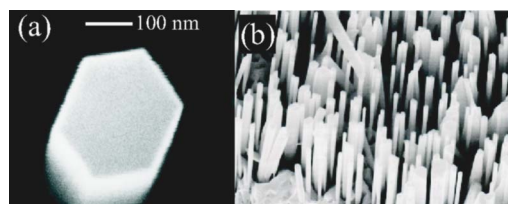

FIG. 1. (Color online) SEM micrographs showing typical GaN nanowires. (a) Top of the nanowire showing the typical hexagonal cross section. (b) As-grown nanowires.

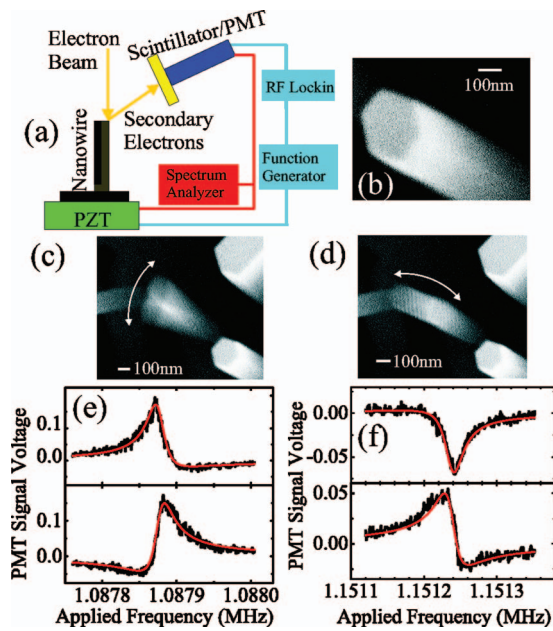a)Electronic mail: shawn.tanner@colorado.edu and shwn_tnnr@yahoo.com

FIG. 2. (Color) (a) Experimental setup for obtaining vibration data from GaN nanowires. Blue lines indicate a scanned frequency mode. Red lines indicate a positive feedback driven mode. (b) SEM micrograph of nanowire used for obtaining vibrational data shown in (c)–(f). [(c) and (d)] SEM micrographs showing resonant vibration of a single Si-doped nanowire. Mode splitting, most probably arising from geometry asymmetries, is evident. (e) Lower frequency resonance curve for the nanowire motion in c with $Q=37\,800$ and $f_0=1.088$ MHz. (f) Higher frequency resonance curve for the nanowire motion in (d) with $Q=37\,300$ and $f_0=1.151$ MHz. Solid red lines indicate a Lorentzian fit to the data.

FIG. 3. (Color online) (a) Scatter plot of Q factor and resonance frequency f_0 vs surface-to-volume ratio. Sample 992 has diameters of less than 100 nm and lengths of ~ 20 μm. Sample 982 has diameters between 100 and 500 nm and lengths of ~ 14 μm and is Si doped. Sample 776 has diameters of less than 100 nm and lengths of ~ 5 μm. (b) Q factor variation for repeated measurements on several nanowires from sample 982. (c) Temperature vs Q dependence for a nanowire from sample 982. (d) Frequency shift due to contamination buildup (carbon, presumably) during e-beam exposure for a nanowire from sample 982. Inset of (d) shows the accumulated deposit of material on the top facet at the end of the nanowire.

tainties, these two techniques yield the same resonance parameters.

For the particular nanowire of Fig. 2, the observed resonance frequency of approximately 1 MHz and the measured nanowire length and diameter allow us to extract Young's modulus of roughly 300 GPa, consistent with reported values for *a*-axis GaN nanowires.[10] Values of $250-350$ GPa are typical for these nanowires, with the uncertainty limited by variations in the nanowire diameter and length. The Q value exhibited by this nanowire ($\sim 38\,000$) is at least ten times higher than previously reported values for *a*-axis oriented GaN nanowires,[10] carbon nanotubes,[14] and single-crystal silicon microstructures of similar surface-to-volume ratio.[8]

We found a range of Q for the ensemble of nanowires and also observed variations in Q upon repeated measurements on the same nanowire. Figure 3(a) shows the Q factor versus the surface-to-volume ratio. Q factors range from ~ 2700 to greater than $\sim 60\,000$. Variations in Q for repeated measurements on five different nanowires are shown in Fig. 3(b). We also find that Q can be increased by almost an order of magnitude by raising the temperature from 325 to 450 K [Fig. 3(c)], perhaps due to the evolution of surface absorbates. This effect has previously been observed on silicon resonators by Yasamura *et al.*[15]

The nanowire-to-nanowire and measurement-to-measurement variations in Q suggest the importance of nanoscale parameter fluctuations in determining resonator linewidths, a conclusion supported by the temperature dependence of Fig. 3(c). One effect, mass loading of the resonator and associated shifting of resonance frequency during the measurement, certainly contributes to the measured linewidths. Figure 3(d) shows the effect of placing the electron
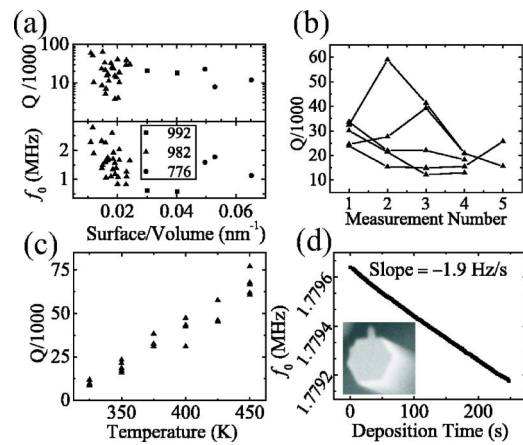
beam on the nanowire for an extended period on the resonance frequency (these data were obtained using a positive feedback mode to be discussed below). The inset shows the appearance of a carbonaceous deposit due to exposure to the e beam. Such mass-loading effects have been previously reported by Buks and Roukes.[16] We estimate that mass-loading accounts for from 5% to fully half of the measured linewidth for the range of nanowires shown in Fig. 3. This effect can be removed by scanning the frequency in both the upward and downward directions to obtain a sharpened and broadened linewidth and using the average to find Q.

We have also observed, during SEM imaging, nanowires that move substantially and even bend into contact with surrounding nanowires and become permanently adhered. This behavior is associated with prolonged exposure of the nanowires to the electron beam. Electrostatic forces can readily become comparable to elastic restoring forces and contribute to the effective spring constant for nanowire vibration. A numerical estimate for nanowires separated by 1 μm indicates that a few thousand static electron charges can shift the resonance frequencies sufficiently to explain the observed resonance widths. Such coupling is sensitive to the separation between the resonance frequencies of the nanowires, perhaps leading to complex behavior as resonance frequencies evolve over time. Many of these effects could be traced to our use of SEM imaging to study the nanowires and may not occur for strictly electronic or optical readout, again suggesting, but not proving, that the observed Q values represent a lower bound on what could be achieved with GaN.

The Q values we observe are comparable to those of commercial quartz crystal resonators used in feedback oscillators. To investigate the behavior of oscillators based on these high-Q nanowire resonators, we closed a feedback loop by connecting the output from the PMT directly to the piezostack [Fig. 2(a), red lines]. The correct phase between the oscillating nanowire and the feedback signal was obtained by positioning the electron beam around the edge of the nanowire. Above a threshold of PMT gain, the system achieved
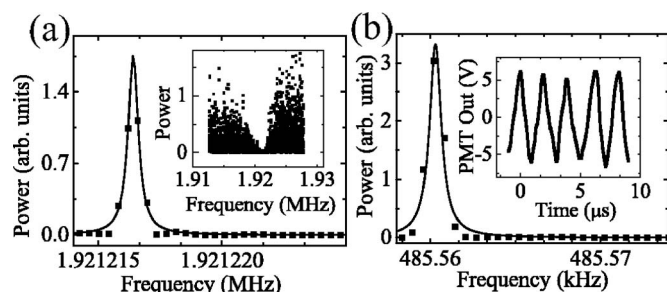
FIG. 4. (a) GaN nanowire oscillation driven by a feedback loop as shown in Fig. 2(a) (red wires). The resonance peak has a Q factor of about 4×10^6. Inset shows the results of positioning the electron beam so that the feedback actively cancels the nanowires motion, resulting in a local dip in the power spectrum at the resonance frequency. (b) GaN nanowire oscillation caused by local e-beam excitation. The solid lines are Lorentzian functions (absolute square of the equation given in the text) that help display the deviations of the data from a Lorentzian line shape. The inset figure shows a time record of the nanowire response. Unintentionally doped nanowires from sample 992 were used to optain this data.

oscillation with a narrow linewidth and a distinctly non-Lorentzian line shape, as shown in Fig. 4(a). These closed-loop oscillations were easy to observe. Further confirmation of the importance of feedback in these measurements is shown in the inset of Fig. 4(a). Here, we moved the electron beam to the opposite side of the nanowire, causing a 180° phase shift between the nanowire motion and the feedback signal (negative feedback). A resulting local reduction in the system noise over a region given by the open loop Q of the resonator can also be seen.

Recognizing that GaN is a piezoelectric material suggests the possibility of achieving spontaneous oscillation by replacing the piezoelectric stack with direct actuation of the nanowire, either by application of electric potential or electric charge. Indeed, we have found that oscillations, essentially indistinguishable from the closed-loop oscillations, can be initiated on the unintentionally doped nanowires without using the external PMT/piezostack feedback loop. By focusing the electron beam on the side of the undoped nanowire, single-frequency oscillations are observed [Fig. 4(b)]. Single-frequency oscillations induced by laser heating have been observed in silicon microstructures,[17] suggesting that the oscillations of our nanowires might be caused by heating from the electron beam. Our inability, however, to observe spontaneous oscillations on Si-doped nanowires, which should have thermal properties similar to those of the unintentionally doped nanowires, implies that the oscillations have another source. We suggest instead that localized charging causes a piezoelectric deformation of the nanowire. The induced motion at the resonant frequency can move the nanowire sufficiently to affect the overlap of the electron beam with the nanowire, thus changing the ability of the electron beam to add charge to the wire and providing a local feedback mechanism.

In summary, we have shown that mechanical resonators fabricated from c-axis oriented GaN nanowires can have high quality factors compared to those of resonators of similar size made from other materials. GaN nanowires have a range of properties that may contribute to the improved Q.

First, the nanowires have crystallographically flat surfaces (as opposed to conventional micromachined silicon resonators[18]) and improved surface conditions, such as lower defect density and reduced oxidation penetration.[12,19] Second, GaN has over twice the density and twice the Young's modulus of silicon, allowing the two materials to have similar resonance frequencies for a given size but giving GaN a distinct advantage in reduced susceptibility to gas sorption/desorption noise.[20] Third, GaN has high heat capacity and thermal conductivity, which make it a favorable material for reduced susceptibility to thermal fluctuations and for improved thermoelastic dissipation limits. These properties, along with the fact that GaN nanowires are piezoelectric and can be grown on silicon, making them compatible with existing processing methodologies, suggest that GaN nanowires may be of increasing importance in nanoelectromechanical systems.

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